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EXPERIENCE WITH SOME REPEAT TESTS ON THE 9" CHORD CAST-10-2/DOA 2 AIRFOIL MODEL IN THE LANGLEY 0.3-M TCT ADAPTIVE WALL TEST SECTION

A. V. MURTHY
Vigyan Research Associates, Hampton, Virginia

and

E. J. RAY
Langley Research Center, Hampton, Virginia

INTRODUCTION

A co-operative testing program is in progress between the Langley Research Center (NASA) and the National Aeronautical Establishment (NAE, Canada) to validate two different techniques of airfoil testing at transonic speeds. The procedure employed is to test the same airfoil model in the NAE two-dimensional tunnel and the Langley 0.3-m Transonic Cryogenic Tunnel (0.3-m TCT). The airfoil model used in testing was CAST10-2/DOA2 super-critical airfoil.

The NAE tunnel has a cross section of 15" x 60", and has conventional perforated walls for the ceiling and the floor. With the airfoil chord length of 9" employed in these tests, the tunnel height/airfoil chord ratio is 6.67. Due to large h/c ratio, the wall interference effects will be small. Hence, wall interference corrections can be applied to the test data with greater confidence.

The Langley 0.3m-TCT has a relatively small cross section of 13"x13", giving a (h/c) ratio of 1.44 for the same 9" chord model. The approach employed in the 0.3-m TCT aims towards eliminating the wall effects by using active walls. The top and bottom walls are flexible. By changing the wall shapes during a test in an iterative manner, the wall interference effects are reduced. The method employed to change the wall shapes was developed by the University of Southampton (England). This method, known as adaptive wall technique originally conceived and tested in the National Physical Laboratory (England), is beginning to find potential application in 2D and 3D transonic testing.

The current test program provided an opportunity to validate the adaptive wall technique in the 0.3-m TCT. The relatively long chord airfoil represents a severe test case to test the efficacy of the adaptive wall technique under cryogenic conditions. The program also involved removal of side wall boundary-layer thus increasing the complexity of the wall adaptation technique. This paper deals with some salient results obtained regarding repeatability of test data and possible residual interference effects.

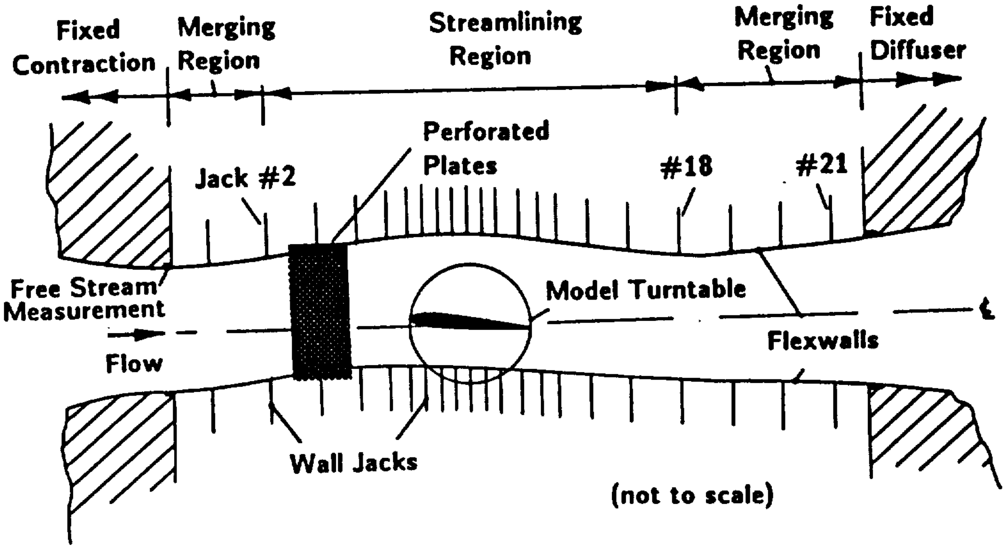
OUTLINE

- **Background**
- **Method: Adaptive wall technique**
  University of Southampton, England
- **Comparison of data from different entries**
- **Side wall boundary-layer removal effects.**
- **Top and bottom wall interference effects**
- **Conclusion**

0.3-m TCT Adaptive Wall Test Section

The 0.3-m TCT adaptive wall test section has rigid side walls and adjustable top and bottom walls. The length of the test section is 67" long. Jacks driven by stepper motors move the top and bottom walls to the required shape during a test. The tunnel reference Mach number is measured near the upstream anchor location of the top wall (x=-31.25"). The test section has provision for removing the boundary-layer on the side walls. The removal location is upstream of the model. The boundary-layer removal region is about 6" wide, and extends from ceiling to floor. The removal medium is a perforated plate. The perforations in the plate were drilled using the electron beam technique. The boundary-layer mass removed from the side walls exhausts to atmosphere through digital flow control valves.

0.3-m TCT ADAPTIVE WALL TEST SECTION



CAST10-2/DOA2 Airfoil test program

The first entry of the CAST10-2/DOA2 airfoil model to the 0.3-m TCT was during November 1986. By then, the tests in the NAE tunnel were over and the corrected data were available for comparison. It was gratifying to note that the 0.3-m TCT test in the relatively smaller test section for the large chord model agreed with the data from the much larger NAE tunnel.

Encouraged by this good agreement, the same model was employed in side wall boundary-layer removal tests conducted about a year later. The purpose of the later test was primarily to examine the wall adaptation process in the presence of side wall boundary-layer removal. The test data, under no boundary-layer removal conditions, were expected to provide a base line comparison with the earlier tests. Surprisingly, the two test data did not agree. The differences were large compared to the test accuracy.

Possible speculations for the differences included facility related hardware and instrumentation problems, or the presence of perforated plates for side wall boundary-layer removal. Further tests by replacing the perforated plates with solid plates confirmed our previous experience that at least the perforated plate was not the cause for the observed differences. It was difficult to identify specific reason(s) for the differences. Therefore, two additional entries (Entry III and IV) were made after a thorough calibration of the instrumentation and careful planning of the test details.

0.3-m TCT ADAPTIVE WALL TEST SECTION

CAST10-2/DOA2 Airfoil Test Program

Entry No.	Tunnel Configuration	Sidewall BL Removal	Test Date	Comments
I	Solid Plate Inserts	–	November 1986	Good agreement with NAE data
II	Perf. Plate Inserts	0 - 1.6%	September 1987	Differences with Entry I data
III	Solid Plate Inserts	–	May 1988	Further Investigation
IV	Perf. Plate Inserts	0 - 1.6%	July 1988	Further Investigation

Test conditions for Entry III and Entry IV

Most of repeat tests were at a Mach number of 0.765 and a chord Reynolds number of 20 million. The model had transition strips (carborundum grit no. 320) on both the surfaces to ensure a turbulent boundary-layer. The objective was primarily to reduce the uncertainty in transition location which can affect the test data.

The side wall boundary-layer removal was in passive mode. The maximum flow removal rate was about 1.6% of the test section mass flow.

MODEL AND TEST CONDITIONS

TEST SECTION

Height, h (Nominal)	: 13.0 inches
Width, b	: 13.0 inches
Top & bottom walls	: Adjustable
Side walls	: Fixed
Boundary-layer removal	: Upstream

MODEL

Airfoil	: CAST10-2/DOA2
Chord	: 9.0 inches
Chord/height (c/h)	: 0.69
Aspect ratio (b/c)	: 1.44

TEST CONDITIONS

Mach number	: 0.765 & 0.78
Reynolds number	: 20×10^6
Transition	: Fixed
Boundary-layer removal	: 0 - 1.6%

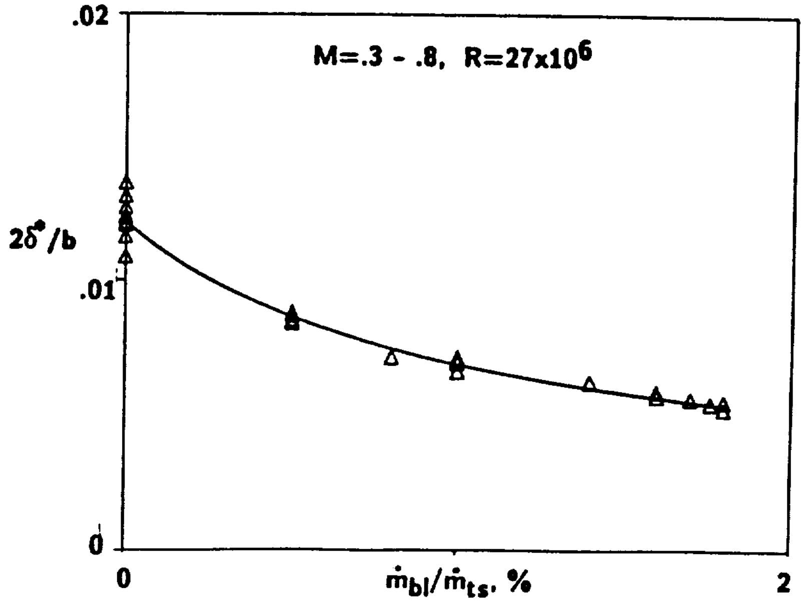
Side wall boundary-layer thickness

The empty test section side wall boundary-layer thickness is a measure of extent of side wall interference on the test data. A boundary-layer rake mounted on the turntable in the empty test section was used to measure the boundary-layer thickness. The measurements showed that the displacement thickness is about 1.3% of the test section width when there is no removal, and reduces to about 0.6% under maximum removal conditions.

The extent of side wall boundary-layer influence will be of the same order in all the entries. Hence, the differences in the test data obtained during different entries will be largely due to residual top and bottom wall interference.

CHANGE IN SIDE WALL BOUNDARY-LAYER THICKNESS AT MODEL STATION WITH UPSTREAM REMOVAL

(Empty test section measurements)

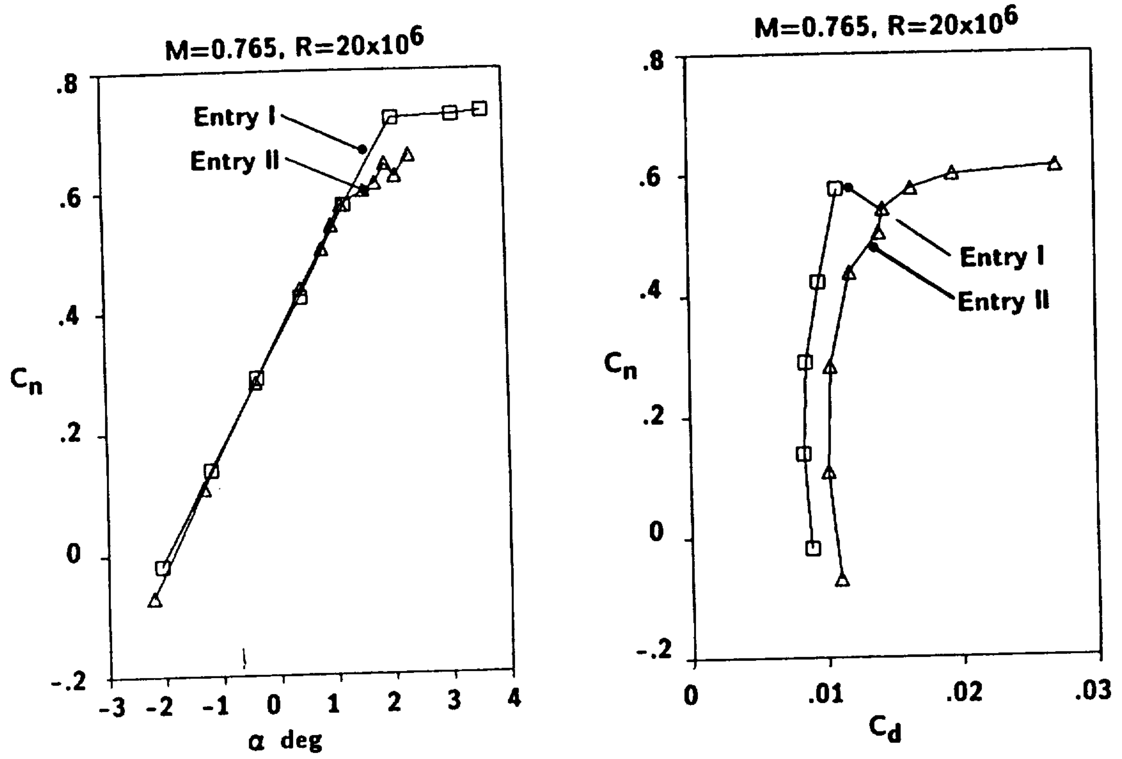


Comparison of data from Entry I and Entry II (M=0.765)

The normal force data at the reference Mach number of 0.765 between the two entries agree closely up to about 1.1 degree angle of attack corresponding to a normal force coefficient of about 0.6. Beyond 0.6, the normal force coefficients are much lower than the values obtained during entry I. However, the agreement up to 0.6 needs closer examination. The corresponding agreement is not reflected in the variation of the drag coefficient. The drag coefficients are consistently higher in the second entry. This suggests the possibility of a higher effective Mach number near the model region, while the reference Mach number in both the tests remained close to 0.765.

COMPARISON OF TEST DATA FROM TWO DIFFERENT ENTRIES

CAST10-2/DOA2 Airfoil (9" Chord)



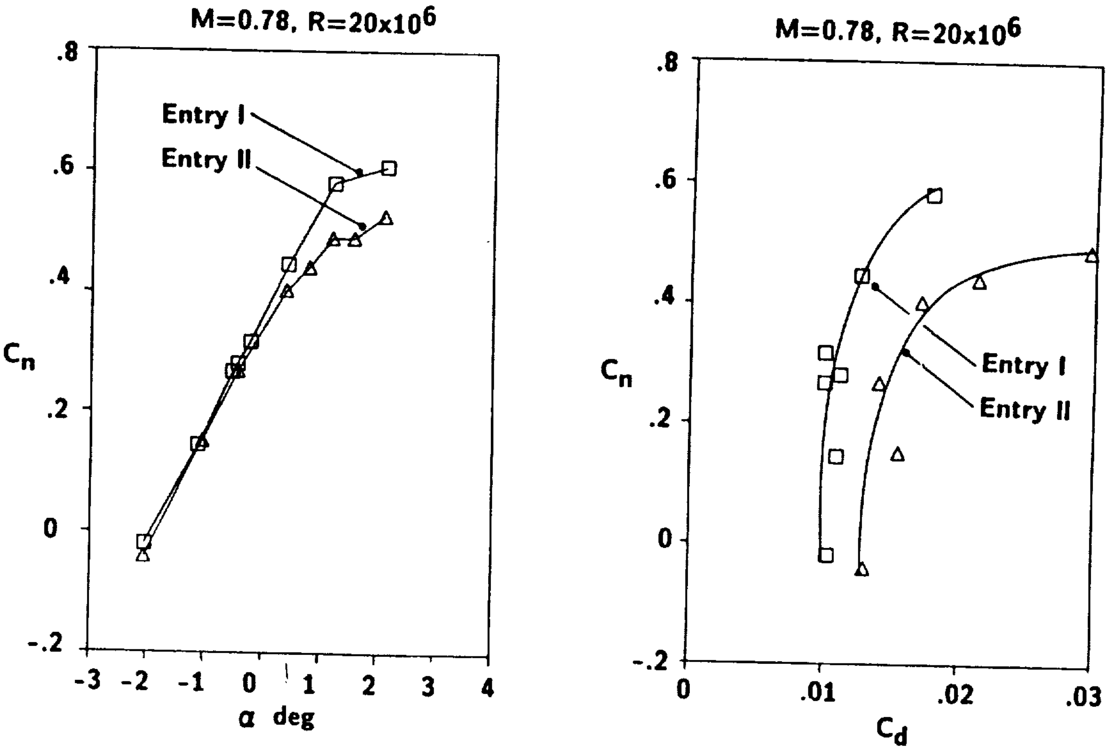
Comparison of data from Entry I and Entry II (M=0.78)

At a slightly higher reference Mach number of 0.78, the same trend is observed for the variation in normal force and drag force coefficients. However, the difference are much larger.

In all these cases, the conditions set for the streamlining of walls were satisfied. This led to the question whether non-unique solutions for wall shapes exist with the adaptive wall testing technique employed. The answer to this question was not simple and straightforward. More analytical and experimental investigation was necessary to determine the cause for the differences between the two sets of data.

COMPARISON OF TEST DATA FROM TWO DIFFERENT ENTRIES

CAST10-2/DOA2 Airfoil (9" Chord)

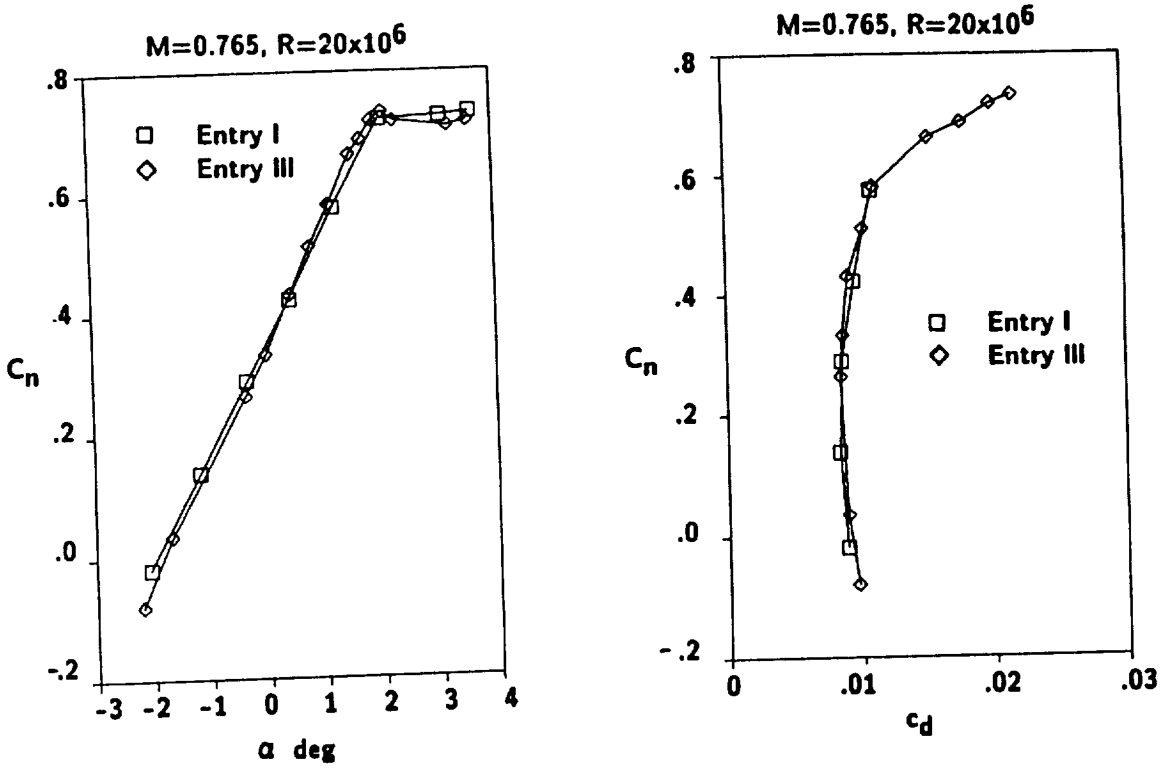


Comparison of test data from Entry I and Entry III

The purpose of the third entry was to reduce uncertainties to the possible extent any facility related hardware and instrumentation problems. The perforated plates used for side wall boundary-layer removal in the second entry was replaced with the solid plate inserts. The pressure instrumentation was recalibrated to ensure the required accuracy standards were met. The availability of an advanced personal computer based pressure, temperature and Mach number controller for the tunnel helped in maintaining steady flow conditions during the test.

With this careful planning of the tests, it was possible to closely repeat the data obtained during the first Entry. In some cases, the iteration process was stopped manually when the wall streamlining accuracy was close to set values, to avoid oscillatory and/or divergence of the solutions. Despite this, the repeatability was quite good. Both the normal force and drag data show good repeatability between Entry I and Entry II. Since the data were at much closer intervals, Entry III data shows clearly the non-linear variation of the normal force with angle of attack.

COMPARISON OF RESULTS FROM ENTRY I AND ENTRY III
CAST10-2/DOA2 Airfoil (9" Chord)

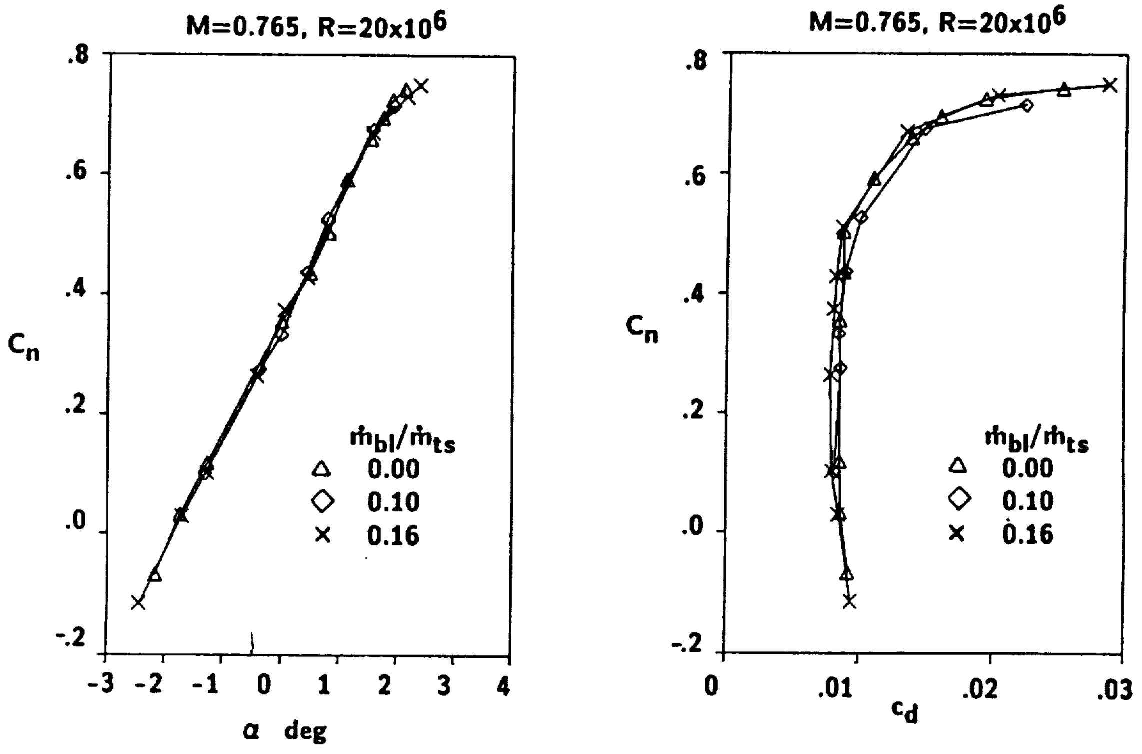


Side wall boundary-layer removal tests

Following the successful demonstration of the repeatability, the perforated plates were reinstalled on the side walls to study the side wall boundary-layer removal effect. Also, we felt it necessary to reconfirm the presence of perforated plates in the Entry II was not the cause for the discrepancy in the test data.

The figures show the normal force and drag coefficient variation for three levels of side wall boundary-layer removal; 0%, 1.0% and 1.6% of the test section mass flow. The iterative streamlining technique worked successfully. The side wall boundary-layer removal did not have a significant effect on the airfoil characteristics. The drag levels appear to be slightly lower for the highest bleed case of 1.6%. However, whether this is really due to side wall boundary-layer effect needs to be ascertained with a detailed assessment of residual interference effect.

SIDEWALL BOUNDARY-LAYER REMOVAL EFFECTS
CAST10-2/DOA2 Airfoil (9" Chord)



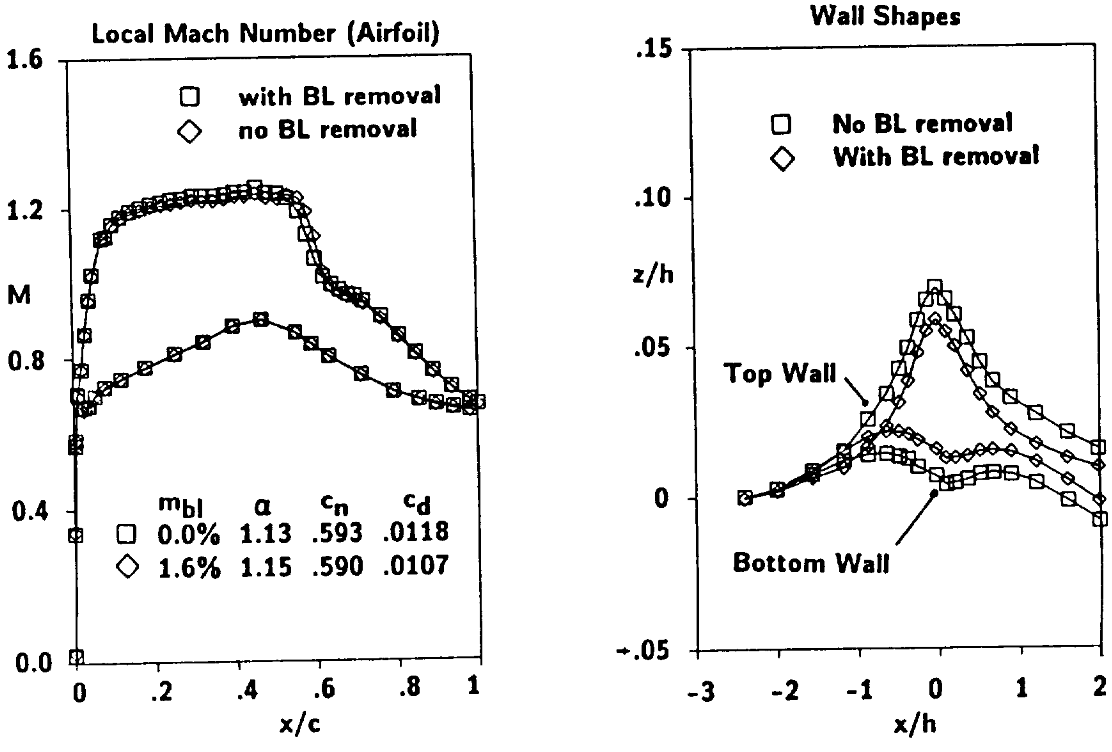
Side wall boundary-layer removal effect on wall streamlining

(Angle of attack: 1.14 degree)

The side wall boundary-layer removal has two effects. First, the boundary-layer thickness at the model station will be smaller. This will reduce the extent of three-dimensional flow field at the airfoil/side wall junction. The force data shows that this effect is not felt significantly at the mid-span where the pressure measurements are made. Second, the free stream Mach number near the model region drops due reduction in mass flow downstream of the boundary-layer removal station. This is an undesirable effect. In conventional wind tunnels, this requires a proper calibration of the test section flow to determine the Mach number correction.

The adaptive wall technique automatically responds to boundary-layer removal effects. Both the top and bottom walls move towards the tunnel centerline to maintain the same upstream reference Mach number conditions in the region of the model. The figure shows the local Mach number on the airfoil and the corresponding wall shapes for conditions with and without side wall boundary-layer removal. While there is no significant effect on the airfoil Mach number distribution, the wall shapes are quite different showing the strong effect of Mach number change due to change in mass flow. Both the top and bottom walls move roughly by the same amount from the shapes corresponding to zero removal conditions. This indicates that the side wall boundary-layer removal is uniform over the height of the test section.

EFFECT OF SIDE WALL BOUNDARY-LAYER REMOVAL
ON WALL STREAMLINING
M=0.765, R=20x10^6,α=1.14 deg



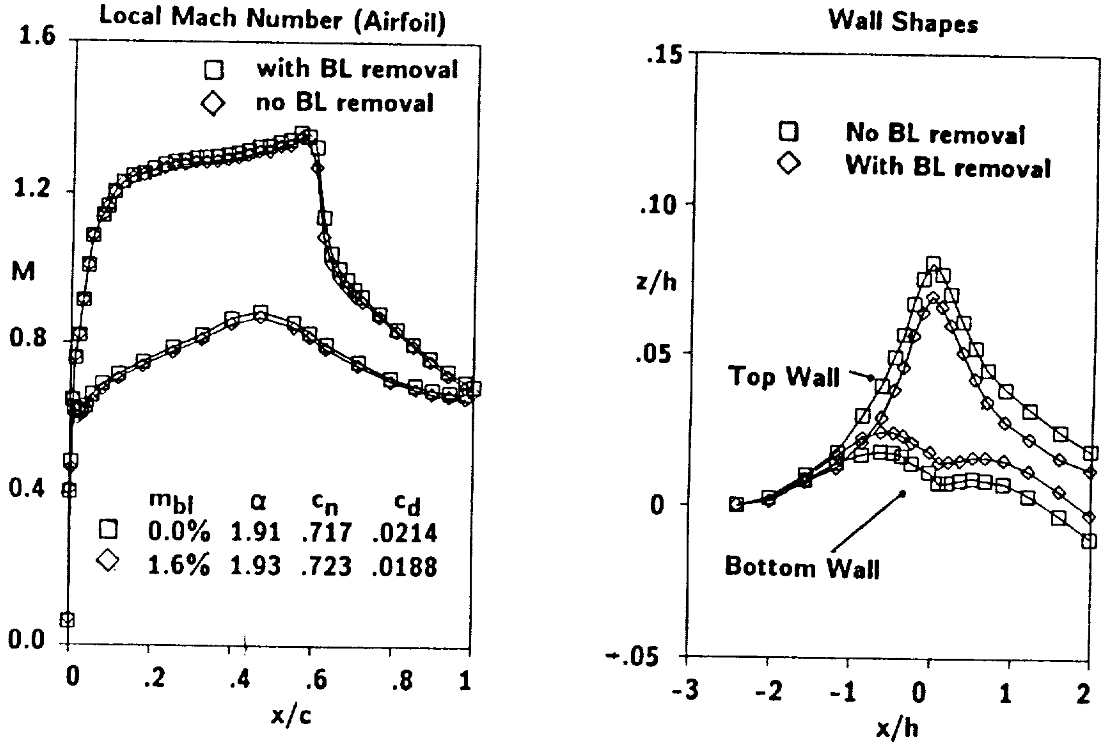
Side wall boundary-layer removal effect on wall streamlining

(Angle of attack: 1.91 degree)

Since the side wall boundary-layer removal does not have a major effect on the airfoil characteristics, the changes in the wall shapes are primarily a function of the amount of mass flow removal only. The airfoil Mach number distribution and the wall shapes at a much higher incidence of 1.91 degrees demonstrate this point. The change in wall shapes from zero removal conditions are about the same as for the 1.1 degree incidence case.

EFFECT OF SIDE WALL BOUNDARY-LAYER REMOVAL
ON WALL STREAMLINING

M=0.765, R=20x10^6,α=1.91 deg

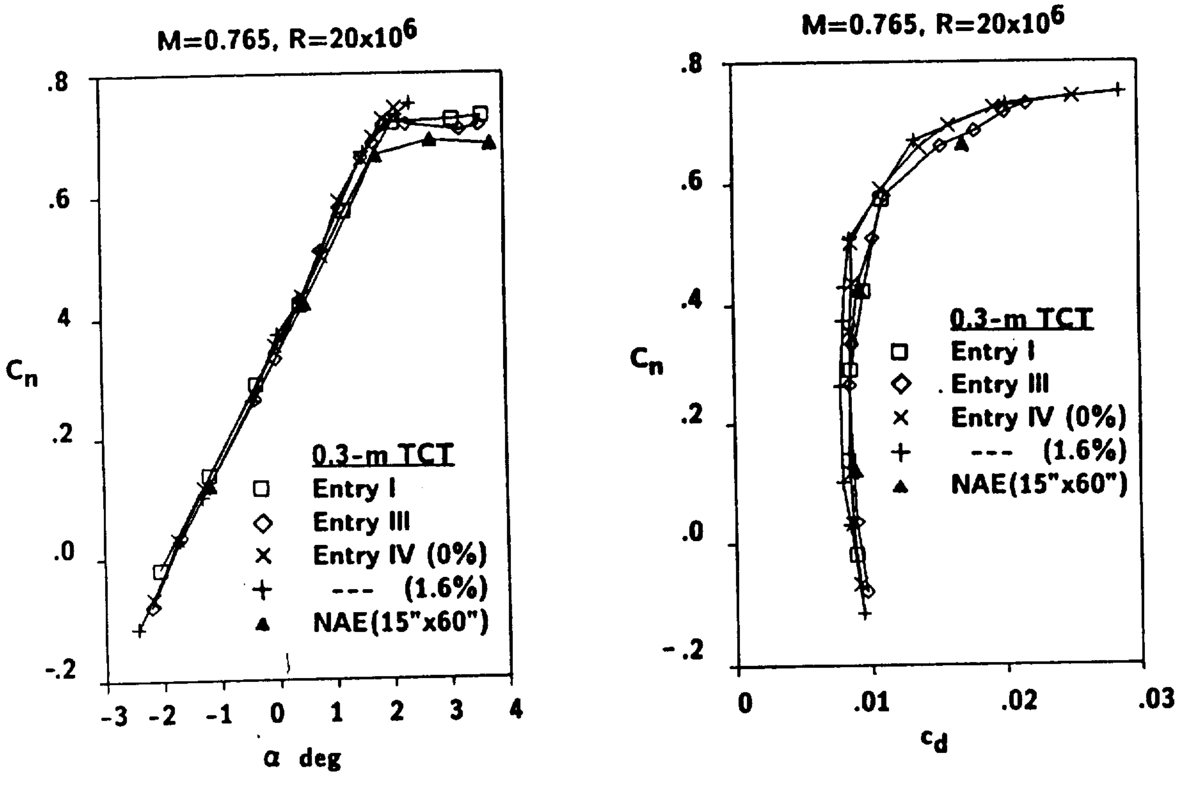


Summary of force data from different tests

(M=0.765, R=20 mil)

The repeatability of the test data over a wide range of varying conditions during different entries is quite good with the adaptive wall technique. The normal force and drag data taken during different entries, with and without side wall boundary-layer removal, agree closely. The data from the NAE tunnel is shown in solid symbols. The agreement between various tests is good. Some differences at higher lifts are quite small and require detailed examination of the test data. It is remarkable to note that the adaptive wall technique employed in the 0.3-m TCT is successful under most complex flow conditions, such as side wall boundary-layer removal, in a fairly smaller test section.

COMPARISON OF FORCE DATA FROM DIFFERENT TESTS
CAST10-2/DOA2 Airfoil (9" Chord)



Further study of differences in Entry II

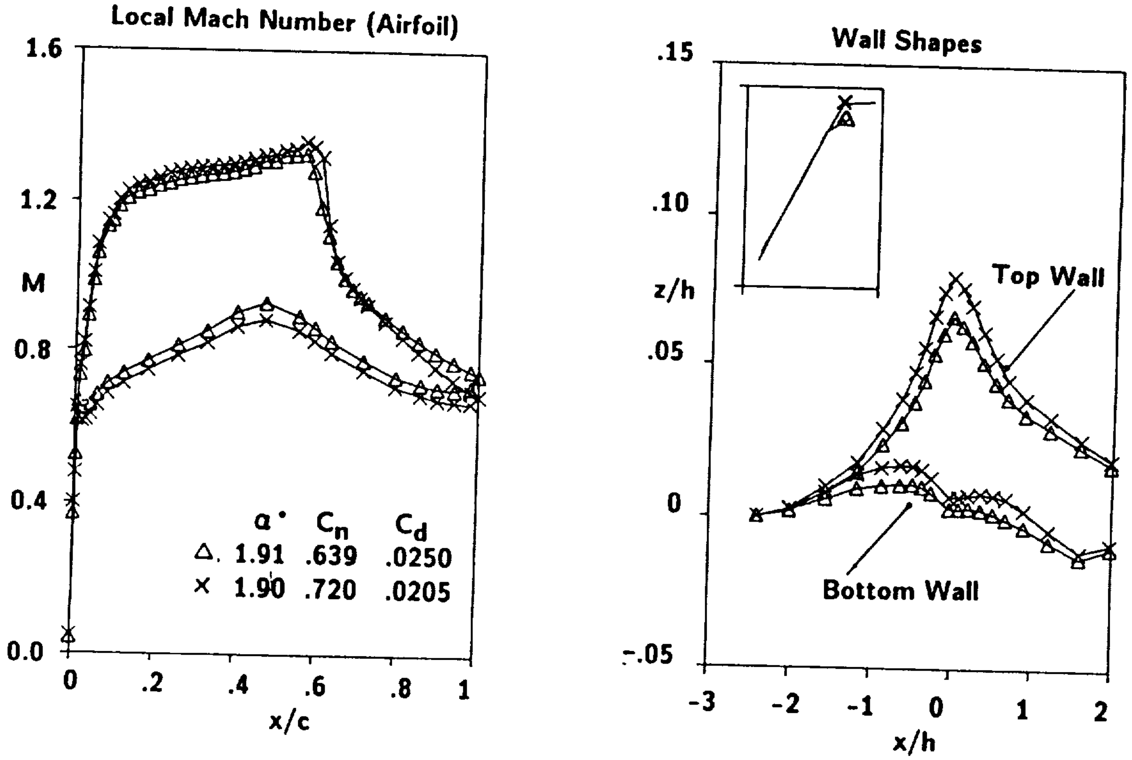
(Comparison of wall shapes and airfoil Mach numbers at 1.90 degree incidence)

The test data taken during different entries proved the repeatability of the adaptive wall technique. However, one question remained unanswered. Whether, the differences noted during the second entry were reproducible. If so, whether the possibly non-unique solutions can be identified during the progress of the test.

To understand the problem, three conditions of angle of attack were considered. The initial wall shapes for these conditions were taken from previous data records.

The first case was at angle of attack of 1.9 degree corresponding to high lift conditions. The wall streamlining process was initiated from previously streamlined shapes. Both had different wall contours and different normal force and drag coefficients. It was surprising to note that for both the wall shapes, the streamlining process converged around the same value. In one of the cases, there is strong indication of trailing edge separation, and also the top wall deflections are less.

COMPARISON OF TWO DIFFERENT SOLUTIONS
$M=0.765$, $R=20\text{x}10^6$



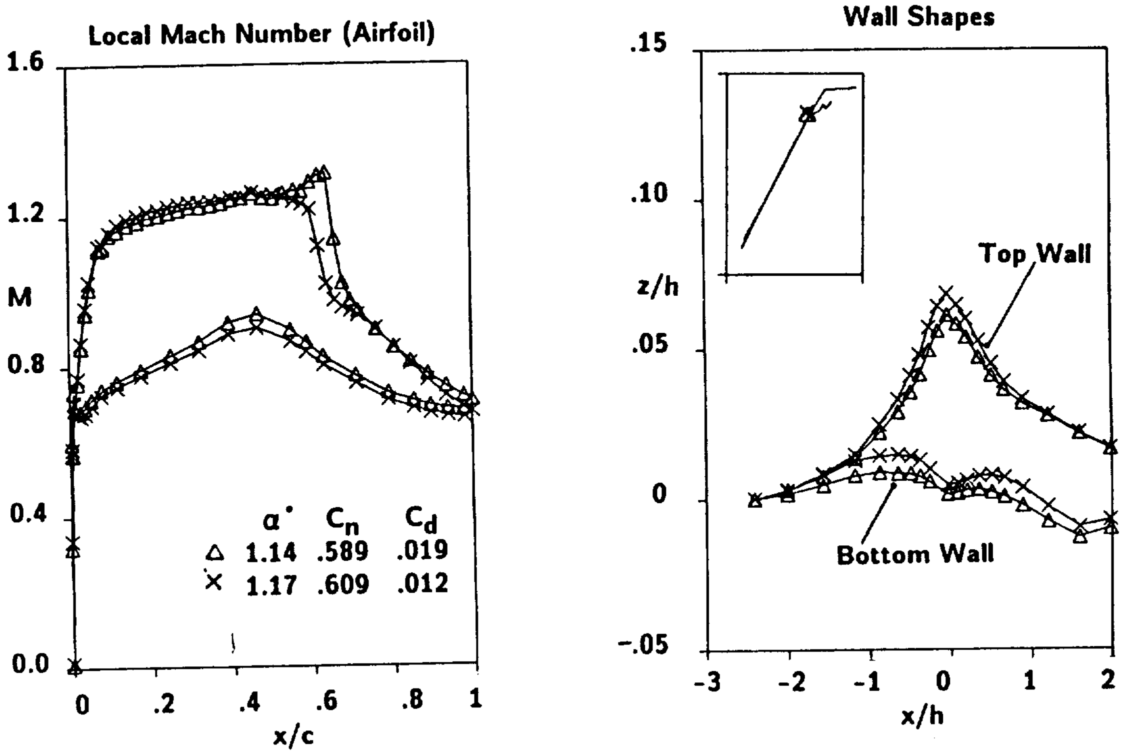
Further study of differences in Entry II

(Comparison of wall shapes and airfoil Mach numbers at 1.10 degree incidence)

The next case considered was at a normal force coefficient of about 0.6, where the Entry II results appeared to break away from the Entry I results. In both the cases the normal forces are about the same value. However, the airfoil pressure distributions are much different. In one of the cases, the shock is much aft and the trailing edge appears to be on the verge of separation. The drag is correspondingly higher. The shock positions are quite different in two cases.

COMPARISON OF TWO DIFFERENT SOLUTIONS

M=0.765, R=20x10^6

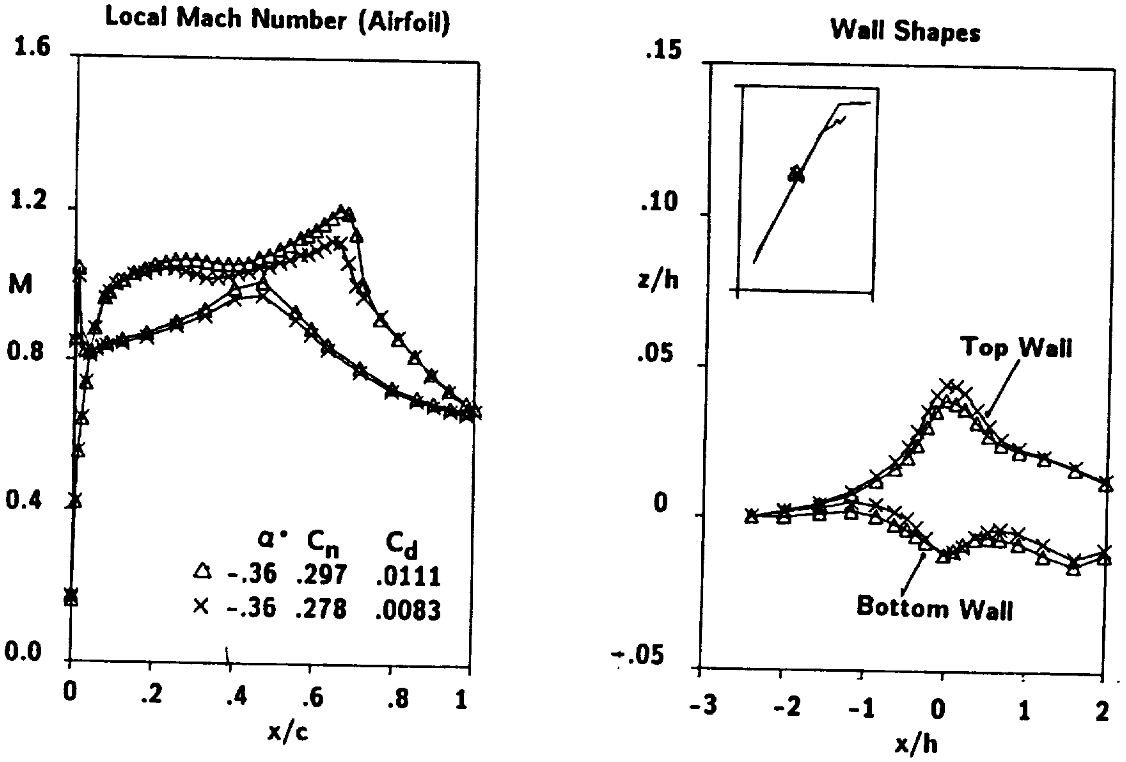


Further study of differences in Entry II

(Comparison of wall shapes and airfoil Mach numbers at -.36 degree incidence)

The next comparison was at a much lower normal force coefficient of about 0.3. There is flow separation at the trailing edge in both the case. Again, the wall shapes and the airfoil pressure distributions are quite different. The local Mach numbers on the airfoil are much higher for the case corresponding to the second Entry initial conditions. The shock appears much stronger with correspondingly higher drag levels.

COMPARISON OF TWO DIFFERENT SOLUTIONS
$M=0.765, R=20\times10^6$

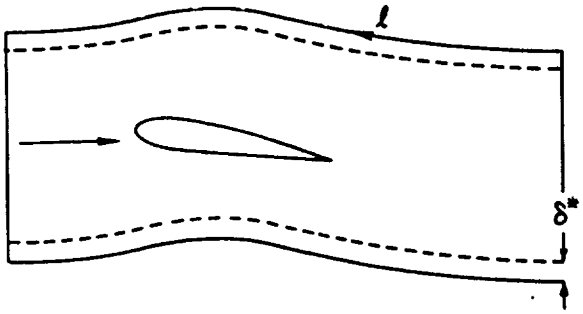


Wall interference assessment

The detailed study of the three cases discussed suggests that the residual interference levels may be different for the two cases, while the wall shapes might have satisfied the required conditions for streamlining. If so, interference assessment will provide an additional tool to reject solutions involving high levels of interference.

The two-variable method based on Cauchy's integral formula, using the flow velocity and inclination at the wall, is particularly suitable for residual interference assessment. The method does not require model description and can take into account the curved top and bottom wall shapes.

WALL INTERFERENCE ASSESSMENT



Interference Velocity

$$W_w(z) = \frac{1}{2\pi i}\int_{\ell} \frac{W(\zeta)}{(\zeta - z)}\, d\zeta$$

$$W_w(z) = \beta u_w - i v_w$$
$$z = x/\beta + iy$$
$$\zeta = \xi/\beta + i\eta$$

- Two Variable Method
- Cauchy's Integral Formula (Ashill & Weeks)
- Applied to Coutoured Walls
- No Model Description Required
- Approximation

  Interpolation at upstream and downstream ends

  Boundary-layer growth not included

Interference corrections:

Blockage: $u_w(x,y) = (1/\beta)\ \mathrm{Re}\ \{W_w(z)\}$

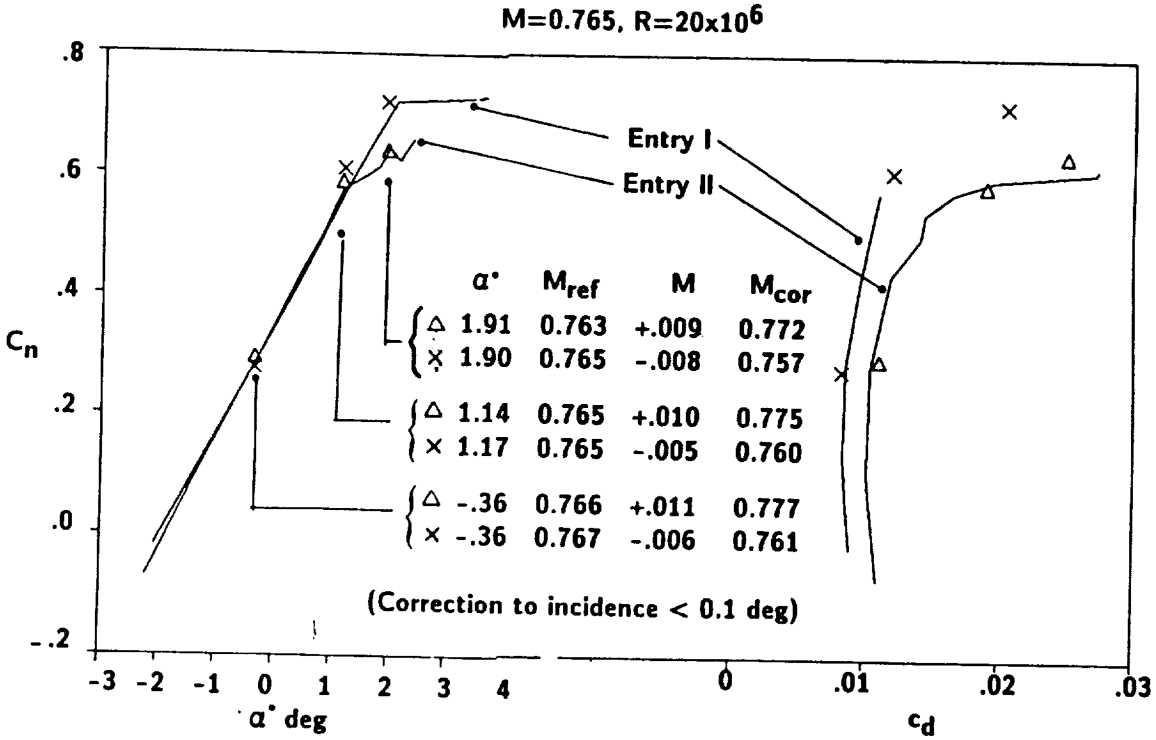
Incidence: $v_w(x,y) = -\ \mathrm{Im}\ \{W_w(z)\}$

Wall interference assessment - Preliminary results

The results of the preliminary calculation using the Cauchy's formula are shown for the three cases discussed earlier. The calculations show that for conditions corresponding to Entry II results the effective Mach number near the model is much higher. The data corresponding to Entry I giving good agreement with the NAE data, has smaller negative corrections. The higher effective Mach number near the model for the Entry II test conditions also explains the higher drag levels.

The above calculations show that the method can identify cases involving high corrections and can be used as an additional tool for assessing the quality of streamlining. The method is amenable for on-line calculations.

WALL INTERFERENCE ESTIMATION



	α°	M_{ref}	M	M_{cor}
△	1.91	0.763	+.009	0.772
×	1.90	0.765	-.008	0.757
△	1.14	0.765	+.010	0.775
×	1.17	0.765	-.005	0.760
△	-.36	0.766	+.011	0.777
×	-.36	0.767	-.006	0.761

(Correction to incidence < 0.1 deg)

CONCLUSIONS

- Repeatability of the test data demonstrated with different tunnel entries.
- Walls streamlined successfully with and without side wall boundary-layer removal on a long chord model (c/h=0.69).
- Side wall boundary-layer removal did not have significant effect on airfoil characteristics.
- Top and bottom walls contracted with side wall boundary-layer removal to correct for change in Mach number.
- Difference in test data between Entry I and Entry II is not due to any extraneous test condition or limitation.
- Present streamlining procedure may lead to wall shapes having excessive blockage interference.
- Cauchy's formula provides a quick estimate of the residual interference and can be used on-line.
- Refinements to the present streamlining procedure will improve long term repeatability of the test data.